RHIC Recovery Review Report

January 22, 2024

1) Findings and Introduction

Introduction

Just after 12:30 PM on August 1, 2023, the RHIC superconducting magnet quench system triggered and consequently the energy dump resistors were switched into the blue ring quad and dipole circuits and the interaction region DX dipole heaters were switched on. This was a spurious trip (there was no actual quench) and was not unusual as the outdoor summer temperature often caused the quench detectors to cause such trips. The collider control room notified the on-duty cryogenics technical staff of the quench trip. A short time later building 1004B cryogenic low-helium and valve box insulation vacuum failure alarms were observed. The cryogenics technical staff observed the cryo-relief line from the blue ring valve box was exhausting helium outside the building.

Upon further examination, the loss of helium and loss of insulation vacuum was traced to a large (2 inch) hole in the magnet current feedthrough system tubing and a hole in the surrounding valve box insulation vacuum bellows. The 12 (each rated for 150A) conductor terminal board D (TBD) feedthrough assembly was found to be badly damaged and covered with soot from burned plastic insulation material. Ten current feedthroughs were vaporized at their soft-solder joint and electrical insulation material covering the feedthrough was heat damaged, indicating that the feedthrough below the solder joint was over-heated.

Following the removal of the failed feedthrough from the magnet circuit, inspection showed ground faults and inter-circuit shorts on the bend, quad, and trim quad magnet circuits. These were traced to the two B4DX splice cans, (located within the magnet cryostat), inside of which all conductor splices were badly heat-damaged and charred. When the conductors were cut and B4DX splice cans (numbers 2 and 3) were removed, all ground faults cleared and no additional damage from this incident is evident. The B4DX magnet will be replaced.

The RHIC team has analyzed signals recorded during the incident and is now preparing and replacing the damaged equipment. Operation is expected to resume in March 2024. The purpose of the RHIC Recovery review is to assess the team's understanding of what happened and identify what else needs to be done before cool-down and magnet circuit re-energization to reduce the risk that this reoccurs.

Background

The RHIC superconducting rings have been in operation for 23 years. Two further experimental runs are foreseen before the collider facility is renewed for the EIC. No previous failure of this sort has occurred. It is important to establish and maintain smooth operation for the remaining RHIC runs to provide an effective final data set for the recently upgraded detectors.

Some RHIC components will be reused for the EIC. This critical cost-saving measure means their lifecycle will be extended by several decades beyond what was foreseen originally during the design phase of RHIC. The Recovery review committee noted possible end-of-life issues, and these are listed in this report as second-tier recommendations, not necessarily to be resolved before restarting.

Purpose of the Recovery Review

On 1 August 2023 the ongoing RHIC operation was halted due to helium outflow through the blue ring valve box relief system in building 1004B. Further investigation revealed magnet electrical buses shorted to ground and a damaged insertion region 4B superconducting DX magnet. RHIC Run 23 ended six weeks early since the preliminary estimated repair time exceeded the remaining run time.

The cause for the valve box and magnet system failure has been investigated, and repair is already under way.

This review is to address 6 charge questions (see Appendix) dealing with the understanding of exactly what happened and identifying the underlying causes, assessing the recovery effort planning, and considering what else might have been missed during the effort.

Magnet systems

The RHIC main 5500A (nominal) dipole and quadrupole buses run out from the power supply halfway around the ring, then loop back around the entire ring, and then come back along the other half of the ring into the return side of the power supply, which is in the 4 o'clock support building. Blue and Yellow ring circuits are separate, and the 12 large, common DX insertion magnets are powered by the blue dipole bus. The dipole bus has three segments that can be fully isolated from one another, one powering the main sextant magnets in the 4/5, 6/7, 8/9 half of the ring, followed by a second powering the insertion dipoles D0 and DX in each of the six insertions, and a third powering the segments on the opposite half of the ring, 10/11, 12/1, 2/3. The quad bus cannot be segmented and powers (in sequence) the QD (V) magnets (4 o'clock to 10 o'clock), QF (H) all around the circumference, and finally the QD in the 10 to 4 sextants. The main power supplies are at the 4 o'clock point and are grounded at the return contact. During a quench, to reduce the peak voltage to ground, the power supply is disconnected from the circuit and a quench-ground, located at the central point in the circuit, is used. It is worth noting that the system ground shifts when a quench is detected, and this can change voltage differences between the quad circuit and the dipole circuit.

Importantly for this review, the quad bus is connected to several nested, or floating, shunt supplies that can add/subtract up to 10% of the main current on selected magnets. The failed feedthrough at TBD carried current for five of these circuits, identified as Q1, Q2, Q3, Q9, and QD. These occupied 11 of the conductors. Since the feedthrough single conductor rating is only 150A, the higher amp shunt power supplies feed more than one conductor (up to four for Q9 in the TBD feedthrough that failed).

The trim circuit leads become superconducting inside the valve box lead pot, which is full of 4.5K supercritical helium and carries the inter-magnet wires that connect across the interaction region. The copper feedthrough conductors are connected through the top of the lead pot and are cooled using helium 'boil-off' gas which is ducted in a helix defined using a coarsely threaded plastic guide mandrel that is fixed within a sheet-plastic sheath. The gaseous helium return is through a conical manifold that is welded to a ceramic feedthrough flange plate and a supporting (strain-relief) flange that in turn is connected to a thin-wall tubing that separates the helium from the insulating vacuum and goes down to the lead pot. The flange is mounted to the top of the valve box and linked to the insulating vacuum through a thin wall formed stainless steel bellows. The flow of conductor coolant is controlled using a valve on the return helium. It is important to note that the coolant flow is not controlled within an active stabilization feedback loop (using for example the voltage drop across the trim leads) but rather it is an open-loop algorithm. A baseline flow offsets the heat conducted down the copper lead towards its junction with the superconductor and as the magnets are ramped, the flow follows the current linearly.

Cryogenic system

Each ring has a large cryogenic valve box in each of the six insertion-region support buildings. Supercritical helium flows from the ring through the valve box and back into the ring through a large vacuum jacketed line. Inside that line the helium duct holds two bundles of 32 superconductors, one for dipoles and the other for quads, (referred to as a cold-crossing bus, CCB).

The valve box iso-vac has a lift-valve type pressure-relief, set to lift around two psig. Most of the escaping helium flowed from lead pot A through the hole in the TBD feedthrough 2-inch diameter guide tube into the large valve box volume, and then outside the building.

Enough helium was released into the valve box through this hole and enough air entered the valve box through the hole in the bellows that the valve box tank itself became quite cold and the large O-ring that seals the lead pot personnel access flange was cracked and split. Vapor clouds coming from cold helium and/or cooled air that had entered the box from above were visibly leaking through the access flange joint via the splits in the O-ring. It appears that there was not enough of this cold gas to cause a serious oxygen deficiency inside the building as most of the cryogens were released through the lift-valve that is ducted to the outside the building.

Unfortunately, this failure mode was not included in the Oxygen Deficiency Hazard (ODH) analysis done initially to define the ODH system requirements for RHIC.

Terminal-board TBD damage

Ten of the twelve TBD conductors melted through (and vaporized for several inches along their length) due to excessive current-heating and/or arcing between adjacent conductors or to ground. The helix mandrel core was badly damaged but does not appear to have burned all the way through. The outer sheet-plastic sleeve that surrounds the mandrel-conductor assembly was destroyed (burned away) for several inches along its length at two points along the circumference (worst along the path of the B4D6 trim conductor). The feedthrough tube rupture and the bellows rupture correspond to one of those points.

The RHIC team believes that an arc-discharge occurred between adjacent quad trim pins 7 and 9 on the terminal board, corresponding to a Qh (trim Q9) and a Qv (trim Q1) trim circuit, respectively, that sit opposite each other on the ring bus, i.e. at a voltage difference of roughly half of the full circuit quad bus voltage drop (200V). It is presumed that this voltage difference across the 0.136 inch distance between conductors in the board was enough to ignite an arc. Inspection indicated that 1) there were sharp features on the outside of the solder-socket assembly and 2) the plastic sleeves around each solder joint may have been damaged. Trim 9 uses four feedthrough conductors (pins 4,5,6, and 7) and a second arc was ignited on the opposing side of the terminal board, between trim Q9 and Q3. The latter arc is near the feedthrough tube rupture and the bellows rupture. An arc was also initiated between pin 7 and pin 1, (Qh trim 9 and the D6 dipole). By connecting the two main buses, the voltage difference in the terminal board increased to over 500V, more than two times nominal.

Telemetry data and reconstructed timeline

The team presented telemetry data showing voltage and current in these various circuits, recorded with 60 Hz (mostly) and 720 Hz sampling rate.

At 11 ms following the Quench Link Interlock (QLI) trip, Q1 and Q9 current showed abnormal increase. This is assumed to represent the onset of the first arc. About 15 ms later the main quad and main dipole buses show an onset of unusual ground current. It is important to note that these are sampled at 60 Hz (16.7 sample spacing). Very large ground current on these circuits was detected 61 ms from the QLI trip time. Seventy-one ms after that (132 ms from the initial fault) the special DX magnet heater system was fired.

Splice can damage

The CCB is connected to magnet wires at the lead-side and non-lead-side of the DX magnet via solder connections inside two splice cans (labelled #2 and #3 respectively). Because the quad trim and dipole circuits were electrically connected at TBD (pins 7 and 1), very large (>500A) current flowed through the D6 trim and Q9 trim solder joints and these were melted in splice cans #2 and #3. The other splice cans in the insertion region 4B circuits (#1 and #4) were not damaged. It is believed that the splice can damage resulted due to the excessive currents passing through solder joints which were not designed to handle such. The two cans closest to the DX magnet (which was quenched by firing heaters) were subjected to heating by the helium stream of the DX quenched magnet, so they very quickly quenched at the solder joints.

Underlying causes

Because of its location, Terminal Board D (TBD) is most susceptible to such failure amongst all the valve box terminal board connections, including those for the Yellow ring. Firstly, it is connected to quadrupole magnets at the start and at the mid-point of the circuit with adjacent pins on the board at the highest possible voltage difference in the circuit. Secondly, it is linked directly to the dipole string (D6) and, in the splice boxes, indirectly to the opposing side of the dipole circuit (DX).

A draft failure analysis, (focused on the 12 x 150A feedthrough), was distributed as part of the review. The analysis concludes that the design and implementation of the solder connection between the copper conductor bars and the sockets that extend from the ceramic vacuum feedthrough connections was the main cause of failure. An extenuating cause is the lack of effective temperature-based control of the helium flow that allowed substantial heating cycles of these solder joints during the RHIC ramp process. During the RHIC magnet ramping, helium flow rate is behind the current ramping so that current feed-through experienced the increases of resistance and peaked at some point, then reduces of the resistance due to the helium flow rate increases. Each time when RHIC magnet ramp, the current feed-through experienced a thermal cycle.

The mandrel helix is attached to the flange and the copper conductor bars fit into axial slots. It is not clear if the conductors are supposed to be fully restrained in the slots and several dimensional flaws (present since fabrication) were shown indicating that the slots were so tight fit around the conductor that some of the helix segments had been broken off. Two of the 12 connections were not damaged, and they were dissected as part of the analysis effort. These were the QD connections (pins 2 and 3).

In summary, 1) the mechanical tension on the solder joints was beyond nominal design practice and cracks were observed on the remaining (2) intact connections, 2) the solder joints were incomplete (i.e. the coverage of solder between the socket jack and filed-down pin plug was much less than design, and 3) the joint was subject to repeated thermal cycles. RHIC operation (4000 hours/year for 23 years) with a full magnet ramp every 10 to 20 hours gives an estimate of 5000 to 10000 thermal cycles. The above combined to create sharp features near the terminal board and these would have reduced the practical hold-off voltage and increased the likelihood of an arc.

Recovery effort

To match the long-range plans for RHIC and EIC, and to make best use of the recent detector upgrades, the RHIC team plan to begin the cool-down process in March 2024. Fortunately, there was a spare DX magnet and a spare feedthrough. These have been tested (warm) and adapted for use in the 4B insertion. Installation (lead-pot soldering) has started, including assistance from technical staff who worked on the original RHIC installation. Magnet installation in the cryostat (still in place) and integration of the cryo-connections (CCB and a new splice can) are to begin in the coming month. The pressure test of the system is planned for mid-January 2024.

ODH system improvements

The ODH analysis done to classify RHIC buildings did not include the observed failure of the large personnel access valve-box flange (~1 meter diameter) under the lead pot. Cold gas or liquid from above caused the O-ring of this flange to fail and the pressure within the valve box pushed gas/liquid out through the failure points (estimated to be 0.3 square inches). The building was not occupied. Upon entry (3:15 PM) there was no indication of oxygen deficiency.

Neither this failure nor the arc-through bellows hole of the valve box iso-vac were included in the tabulation of ODH. When properly included, with the original (non-credited) controls in place, the ODH was estimated to be level 2. Per policy, ODH level 2 must be mitigated with the application of credited controls. Planning for these controls (high-reliability exhaust fans etc) is underway and installation will be complete before cryogenic operation restarts.

2) Comments

1) The current feedthrough soft-solder joint might be NOT correct in the lead design. The 90 mil square rod is hand-filed to shape and inserted into the hole of the cylindrical rod upside-down so when the joint reached melting point of the soft solder (which for this tin/silver solder is 221C), the soft-solder will flow out (dripping down) easily. As shown below, once the solder flows out, the contact resistance of the joint will increase and more heat will be generated until the arc starts and melt away the copper rod. See the table below.

Table 1: Ohmic heating in the TBD conductor with 150, 500, 1000, 1500, 2000 and 5000A

Round conductor	Normal operation	Abnormal 1	Abnormal 2	Abnormal 5	Abnormal 4	Abnormal 3		
Rod diameter	0.156	0.156	0.156	0.156	0.156	0.156	in	
Rod diameter	3.9624	3.9624	3.9624	3.9624	3.9624	3.9624	mm	
X-sectional area	**12.33123321**	**12.33123321**	**12.33123321**	**12.33123321**	**12.33123321**	**12.33123321**	mm^2	
Length	10	10	10	10	10	10	in	
Length	254	254	254	254	254	254	mm	
Resistivity	2.00E-08	2.00E-08	2.00E-08	2.00E-08	2.00E-08	2.00E-08	Ohm-m	60 C
Resistance	4.12E-04	4.12E-04	4.12E-04	4.12E-04	4.12E-04	4.12E-04	Ohm	
Current	150	500	1000	1500	2000	5000	A	
Joule heating	**9.27E+00**	**1.03E+02**	**4.12E+02**	**9.27E+02**	**1.65E+03**	**1.03E+04**	W	
Volume	3132.133236	3132.133236	3132.133236	3132.133236	3132.133236	3132.133236	mm^3	
Q_dot	2.96E-03	3.29E-02	1.32E-01	2.96E-01	5.26E-01	3.29E+00	W/mm^3	
Q_dot	**2.96E+06**	**3.29E+07**	**1.32E+08**	**2.96E+08**	**5.26E+08**	**3.29E+09**	**W/m^3**	

For 1000 A, the peak temperature in the feedthrough conductor is estimated to be 341 C and for 500 A, 101 C. (See attached slides.)

2) The repeated thermal cycling associated with RHIC ramping will exacerbate effects associated with construction flaws, such as cold-solder joints and physical interferences. These were evident in the autopsy and may not have been noted as part of the initial fabrication checks. Using a direct feedback cycle that controls the flow of coolant directly based on what is needed to stabilize the terminal board connections and leads would naturally reduce the stress. It was pointed out that this may lead to ice-ball formation since the recovery plumbing is not properly isolated or heat-exchanged to room-temperature. This should be further studied, and with the experience of this event, priority should be given to lead stabilization.
3) It is believed that the splice can damage resulted due to the excessive currents passing through solder joints which were not designed to handle such. The two cans closest to the DX magnet (which was quenched by firing heaters) were subjected to heating by the helium stream of the DX quenched magnet, so they very quickly quenched at the solder joints. Nevertheless, no specific corrective measures have been applied to the splice can reconstruction. Assuming that ohmic heating caused by a short circuit at TBD was the cause of the apparent combustion of the insulating material inside the splice box, it might be practical to estimate what sort of connection (and insulation) would be required to increase the thermal resilience of the splice can, thereby reducing the damage incurred by such an event in the future. One suggestion is to increase the current carrying capacity within the splice can so that another (specific) part of the circuit can act to absorb the heat better.
4) The Noryl provides the mechanical support for the leads, per the design. Either because of assembly errors or fabrication flaws, (or design dimensional call-out), this function may not have been properly realized. Given this incident, and the evident role that the conductor support had, this should be remodeled for the EIC application. It is likely that the Noryl should be modified / redesigned.
5) Repeated QLI caused by cabling should have been more thoroughly addressed. This kind of temperature-related electrical wiring instability can be corrected by using more

robust signal connector hardware. Such events add up over the machine lifetime to a major impact on operational performance, beyond causing technical risk such as that seen in this incident.

6) Analysis of this incident would have been clearer with higher sampling (i.e. 720Hz) recorders. This adaptation (standardization) should be considered and made a requirement for future construction.
7) The bellows rupture and O-ring crack were not correctly foreseen in the ODH assessment table. This points to a major flaw in the very basic process of hazard tabulation. Has there been any effort by the team to understand why this particular hazard was overlooked? It seems that bellows rupture should always be included. As part of the ESH feedback cycle, there should be a re-evaluation of the process of ODH assessment table development. This would be a benefit to other labs and organizations who have adopted the very same process.

3) Recommendations

1. Do not make the connection of the D6 circuit to the cold crossing bus in the first splice can location.
2. Continue to review the quench detector and PS DAQ signal to better improve the timeline of Arc in both the TBD lead and the two DX splice Cans. Splice can signal analysis should be as thorough as the TBD lead analysis. (Voltage tap data may prove useful.)
3. Add fuses (with resistor across them) to limit the maximum quench ground currents in both the Quad and Dipole quench grounds. This should be done for both Blue and Yellow rings. Have a separate review of a detailed circuit analysis of the fuse operation.
4. Consider doing a circuit analysis model of combined Blue dipole and quad ring circuits to confirm scenarios of the arc faults. These models can be used to fill in gaps in quench detector signals coverage.
5. Better estimate the maximum temperature reached by the current lead, based on voltage measurements and finer temperature distribution model than “average”.
6. Revise open-loop control algorithm of current lead cooling flow, or better, consider closed-loop control based on current lead resistance measurement.

Additional Recommendations:

For EIC the following recommendations to be considered:

1. It should be explored that the QF and QD buses be separated at 10:00 valve box for high pot testing to confirm electrical isolation between the QF and QD. This would allow high pot testing during startup of the rings

2. Thermal cycling and fatigue could be one of the reasons for this failure. In view of using these magnets for the EIC, the splice cans, valve boxes and lead interconnects should be reviewed thoroughly.
3. Upgrade data acquisition system by implementing faster sampling.
4. Develop a mechanism to prevent MLI from being blown out of the relief valve. That may cause clogging and reduce relief effectiveness.

Appendix:

A) Review Charge and Question Responses from Review Committee:

On 1 August 2023 the ongoing RHIC Run-23 was halted due to helium leaking from the Building 1004B valve box. Further investigation revealed electric buses shorted to ground and a damaged superconducting DX magnet. The RHIC Run-23 ended six weeks early since the preliminary estimated repair time exceeded the remaining run time.
The cause for the valve box and magnet failure has been investigated, and the repair is already under way.
Please address the following charge questions:

a. Does the reconstructed event sequence explain the observed electrical signals and the damage observed in the valve box and DX magnet?
   •*Yes. There is a credible scenario. The DX magnet (splice-box) event sequence reconstruction needs further work*
b. Are the underlying causes understood well enough to assess the probability of this or a similar failure recurring, and have possible mitigation measures been evaluated?
   •*Partially. The scenario presented seems to be well understood. The yellow ring 1004B valve box may have the same problem (minus the D6 lead).*
c. Is the repair plan for the valve box sound and the schedule estimate realistic?
   •*Yes. The repair schedule seems realistic and the repair plan seems to be sound.*
d. Is the repair plan for the DX magnet sound and the schedule estimate realistic?
   •*Yes. The repair schedule seems realistic and the repair plan seems to be sound.*
   •*The plan should include disconnecting and abandoning the unused D6 lead. This incident would have been far less damaging with the D6 connection*
e. Are there further items that must be addressed?
   •*Yes. See Recommendations.*

B) Review Committee:

George Ganetis

Yuenian Huang
George Mahler
Phillipe LeBrun
Renuka Rajput-Ghoshal
Marc Ross (chair)

C) Terminal Board TBD lead thermal model (attached slides from Yuenian Huang)